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Ramachandran et al.

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(54) **SECURITY SYSTEMS AND METHODS TO REDUCE DATA LEAKS IN ENTERPRISE NETWORKS**

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(52) **U.S. Cl.**
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CPC G06F 21/577; G06F 21/554; G06F 21/56; H04L 63/1408; H04L 63/1433; H04L 63/20
USPC 726/19, 22–25, 27, 28; 707/687
See application file for complete search history.

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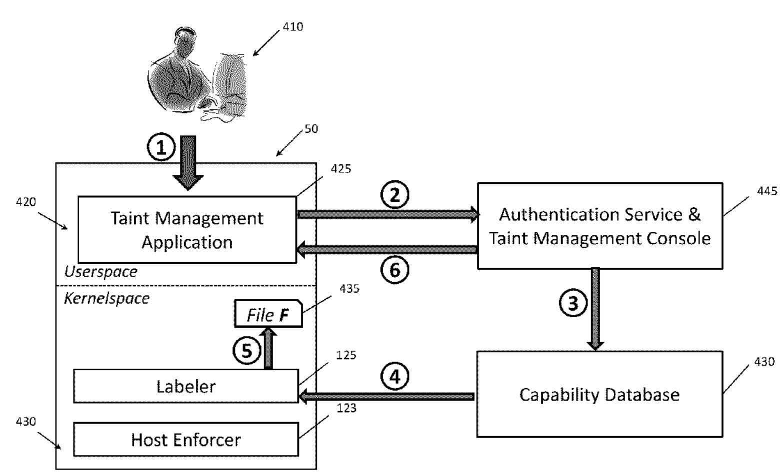
(57) **ABSTRACT**

Disclosed are embodiments of a security system for reducing data leaks by checking information flows between resources of a network. When an information flow is attempted between a sending resource, which can be anywhere in the network, and a receiving resource residing at a specific host within the network, a host labeler can determine whether information is allowed to flow from the sending resource to the receiving resource. The sending resource and the receiving resource can each have an applicable label, and each label can comprise zero, one, or more taints. For each taint having an active secrecy characteristic in a label of the sending resource, the host labeler can require that there be a matching taint with active secrecy characteristic in the receiving resource. If this condition is not met, the security system can block the information flow between the sending and receiving resources.

16 Claims, 7 Drawing Sheets



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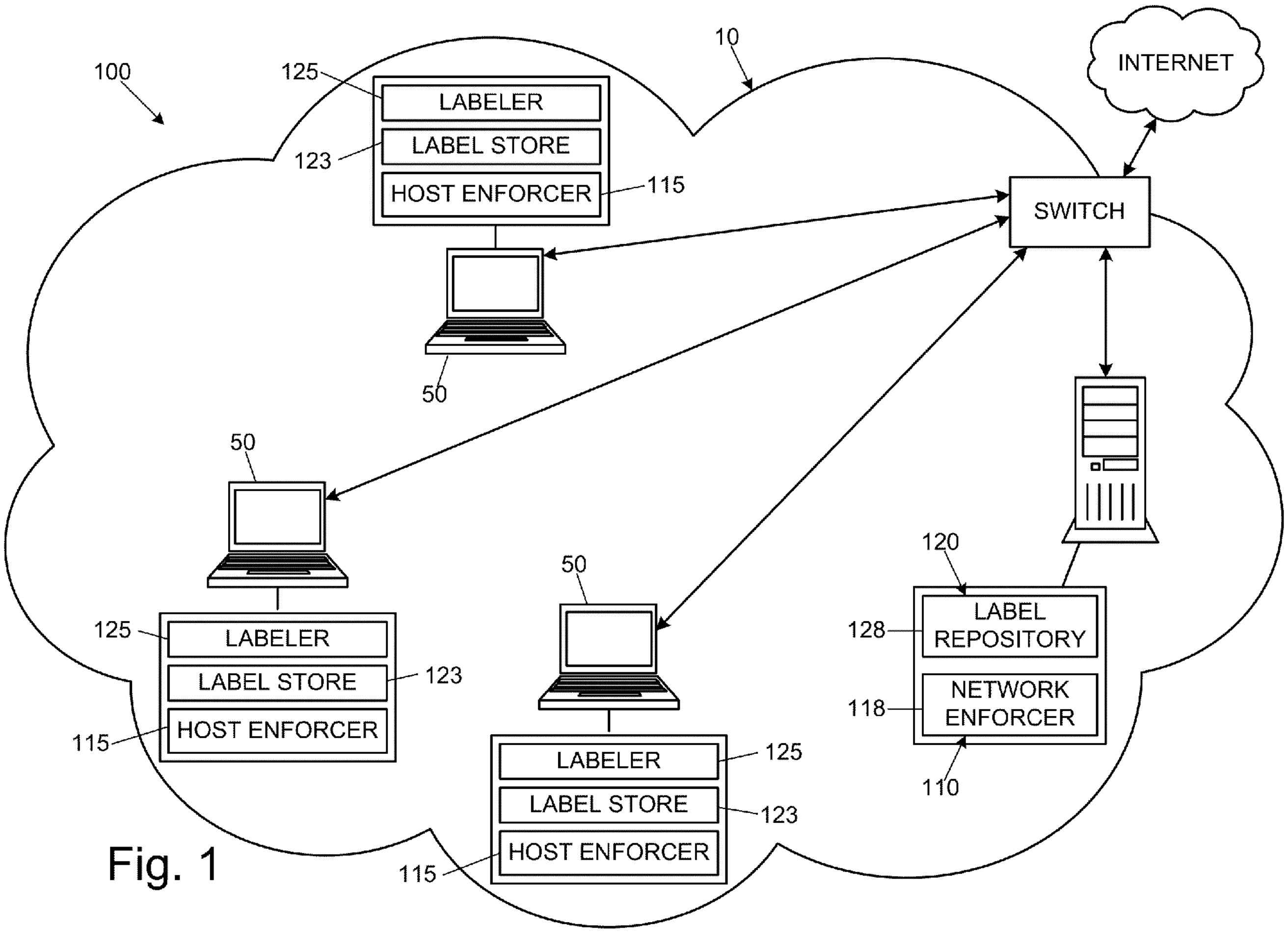

100
10
INTERNET
125
LABELER
123
LABEL STORE
HOST ENFORCER
115
SWITCH
50
50
125
LABELER
LABEL STORE
123
115
HOST ENFORCER
50
LABELER
125
LABEL STORE
123
115
HOST ENFORCER
120
128
LABEL
REPOSITORY
118
NETWORK
ENFORCER
110

Fig. 1

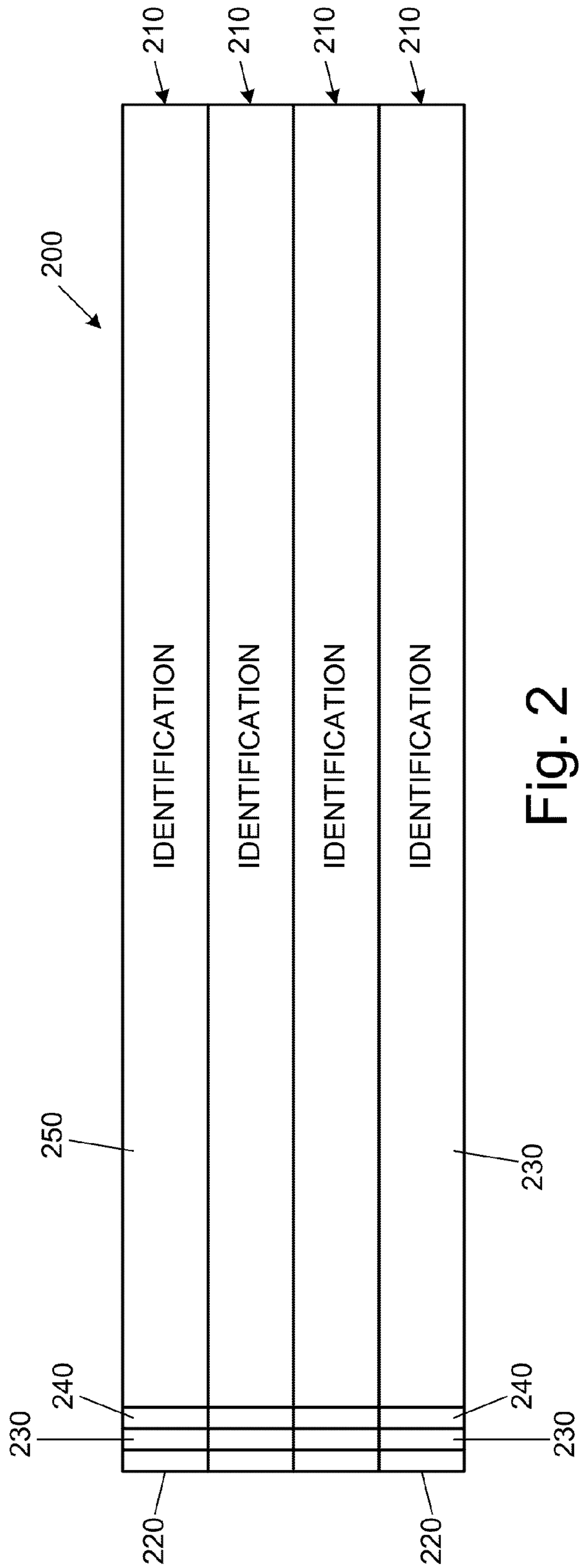
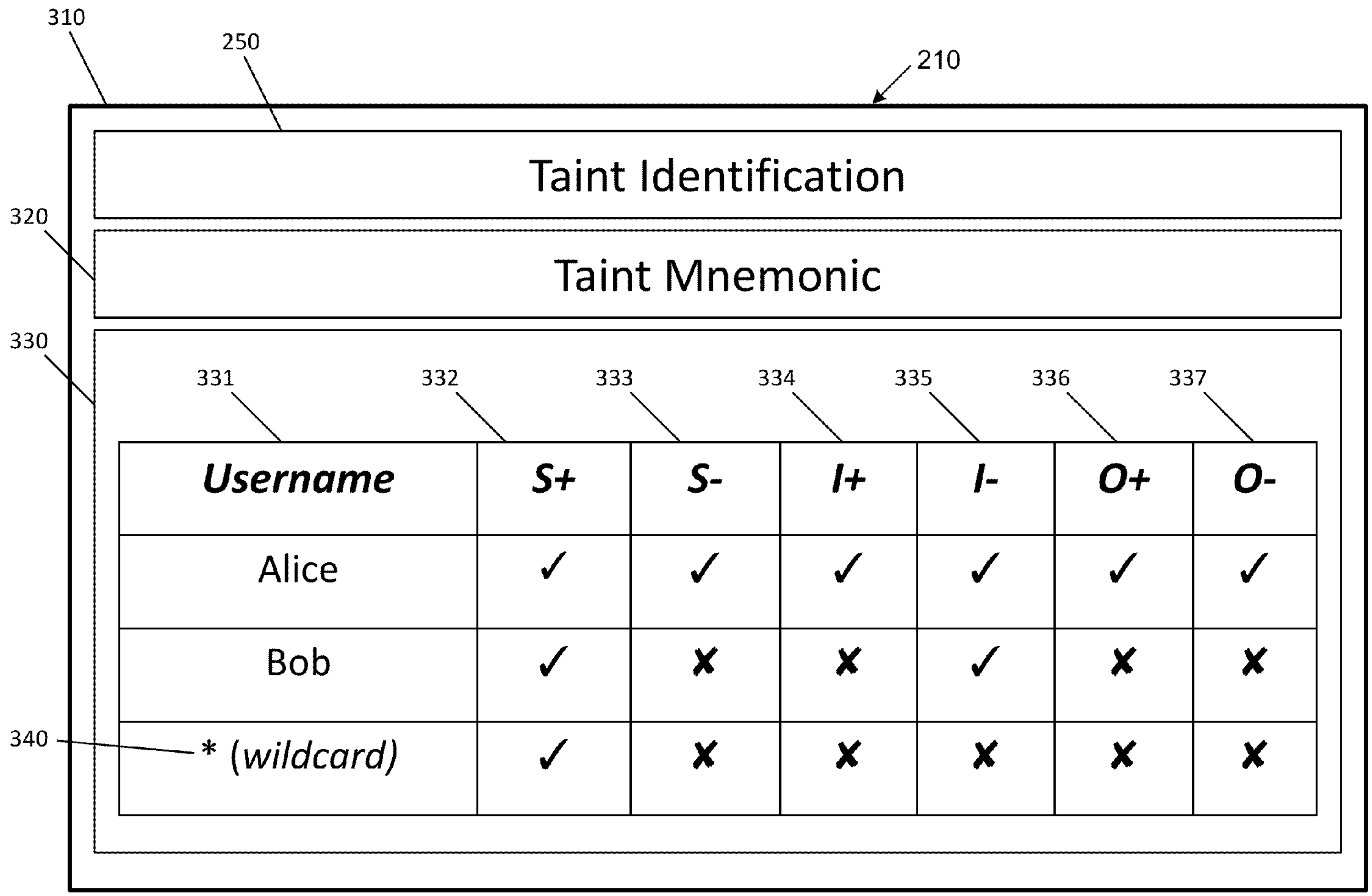

210
210
210
210
200
IDENTIFICATION
IDENTIFICATION
IDENTIFICATION
IDENTIFICATION
250
230
240
240
230
230
220
220

Fig. 2



Username	S+	S-	I+	I-	O+	O-
Alice	✓	✓	✓	✓	✓	✓
Bob	✓	✘	✘	✓	✘	✘
* (wildcard)	✓	✘	✘	✘	✘	✘

Fig. 3

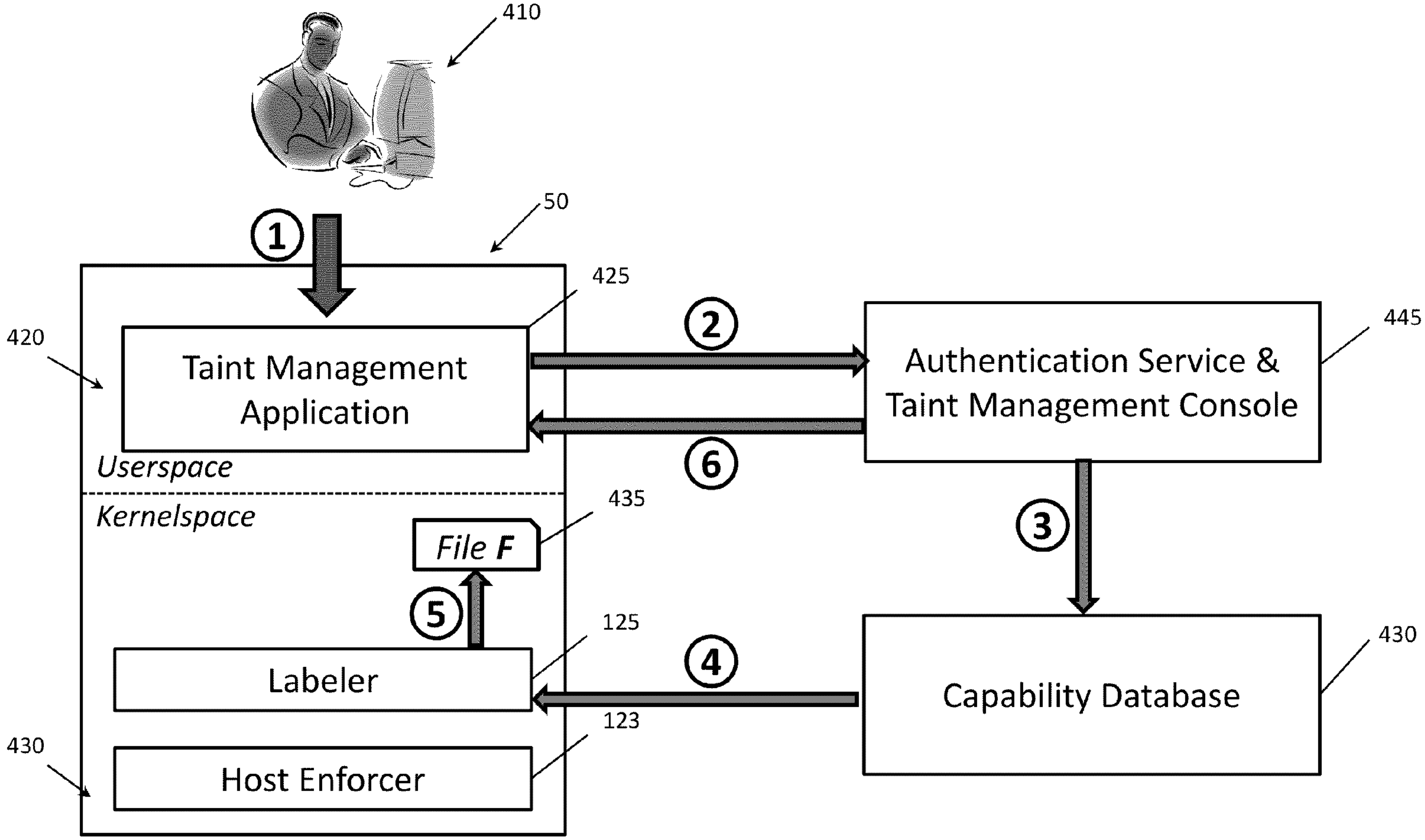

410
50
1
425
420
Taint Management Application
2
Authentication Service & Taint Management Console
445
6
Userspace
Kernelspace
435
File F
3
5
125
Labeler
4
Capability Database
430
123
430
Host Enforcer

Fig. 4

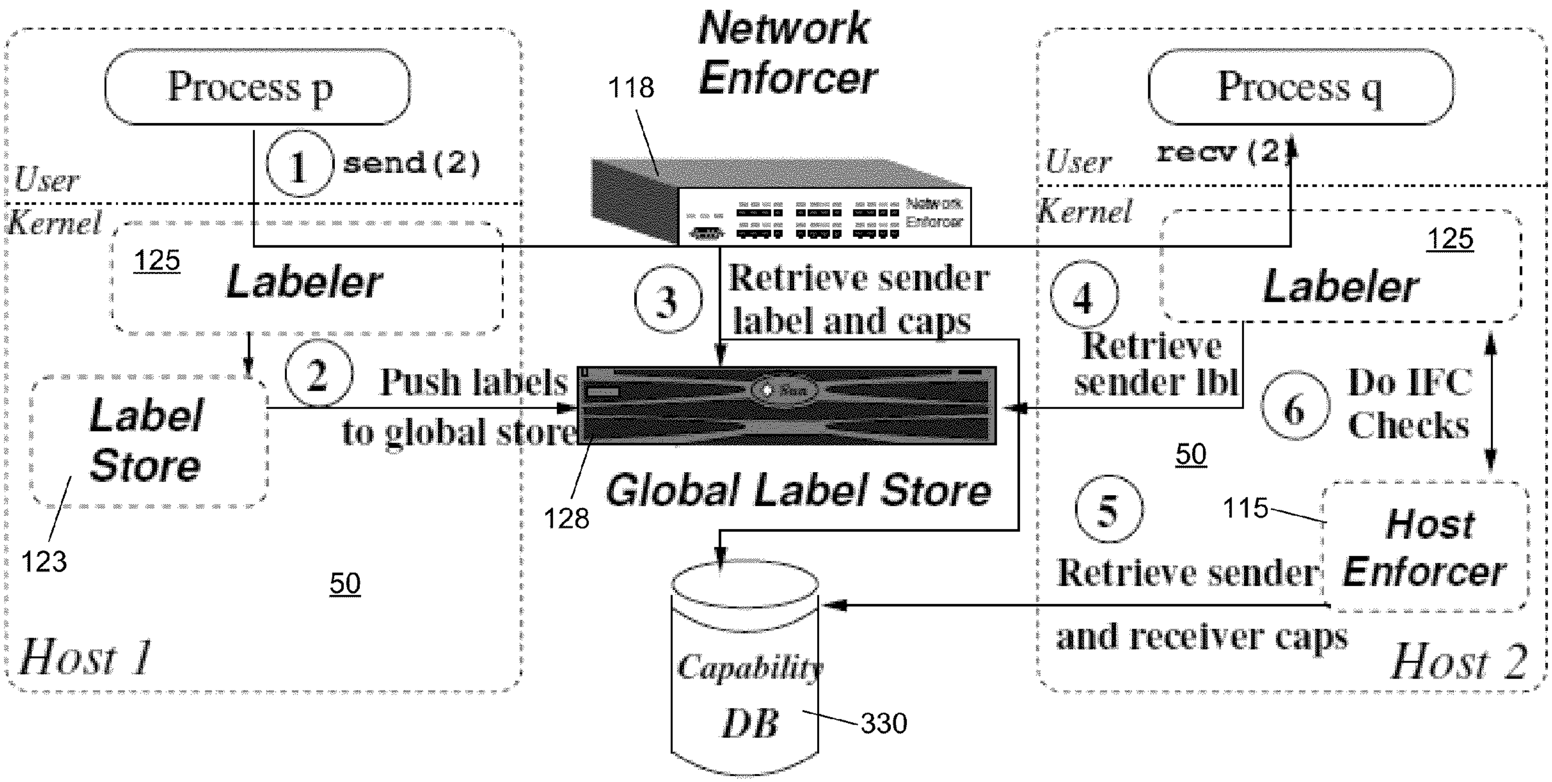

Network Enforcer
118
Process p
1
send(2)
User
Kernel
125
Labeler
2
Push labels to global store
Label Store
123
50
Host 1
3
Retrieve sender label and caps
128
Global Label Store
Capability DB
330
Process q
recv(2)
User
Kernel
125
Labeler
4
Retrieve sender lbl
6
Do IFC Checks
50
5
Retrieve sender and receiver caps
115
Host Enforcer
Host 2

Fig. 5

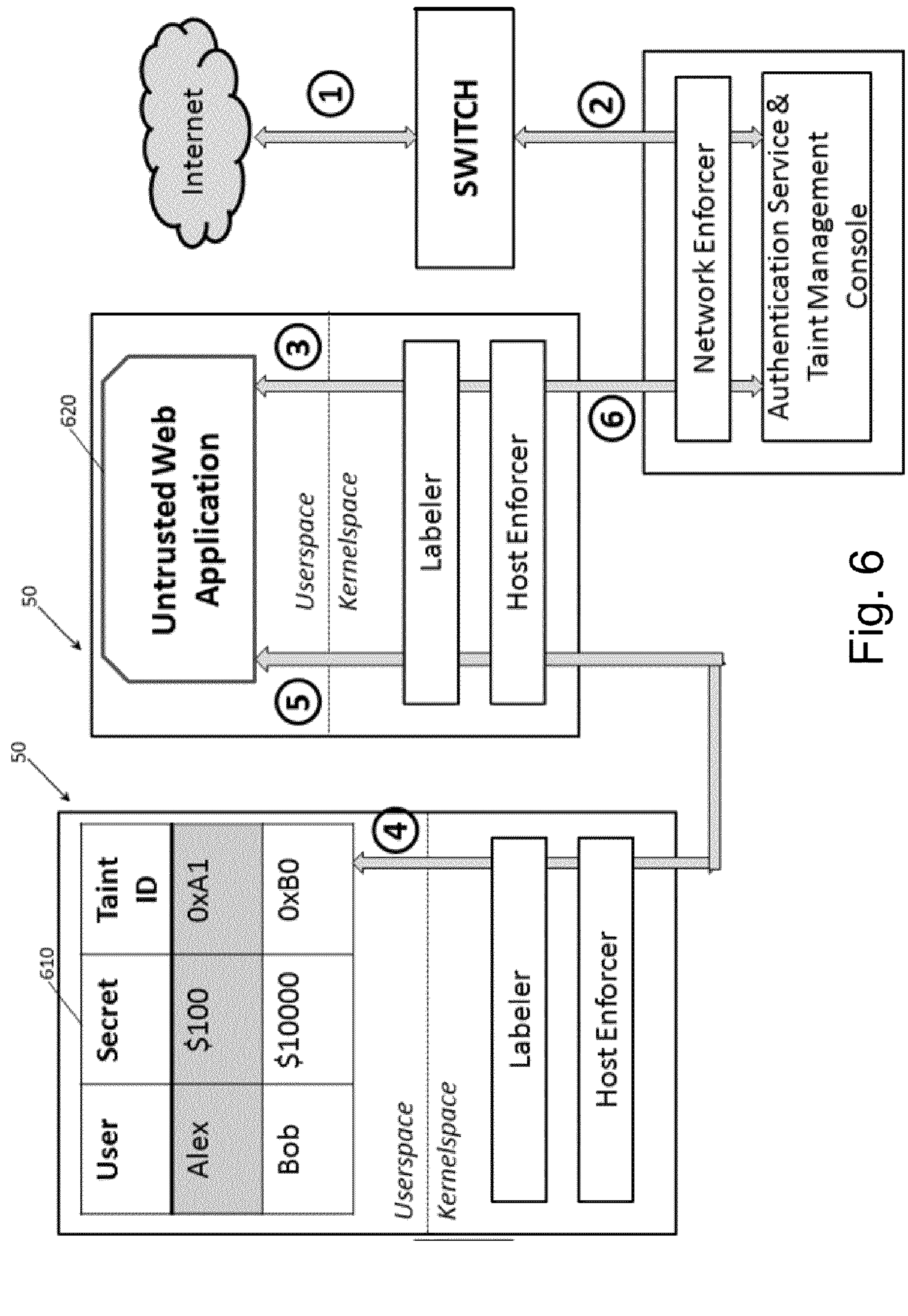
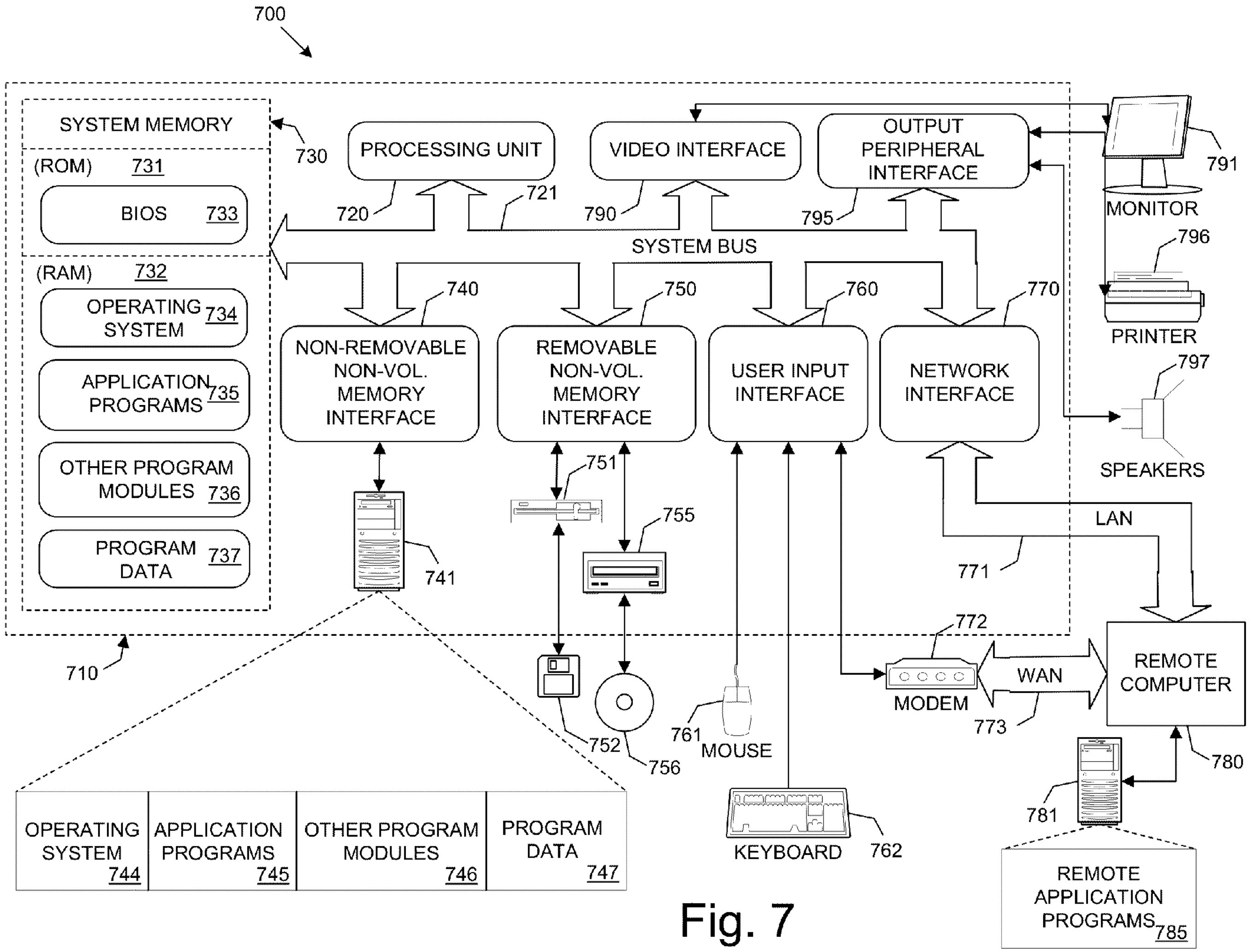

Internet
1
SWITCH
2
Network Enforcer
Authentication Service & Taint Management Console
50
620
Untrusted Web Application
3
5
6
Userspace
Kernelspace
Labeler
Host Enforcer
50
610
User
Secret
Taint ID
Alex
$100
0xA1
Bob
$10000
0xB0
4
Userspace
Kernelspace
Labeler
Host Enforcer

Fig. 6



700
SYSTEM MEMORY
730
(ROM) 731
BIOS 733
(RAM) 732
OPERATING SYSTEM 734
APPLICATION PROGRAMS 735
OTHER PROGRAM MODULES 736
PROGRAM DATA 737
PROCESSING UNIT
720
721
VIDEO INTERFACE
790
OUTPUT PERIPHERAL INTERFACE
795
SYSTEM BUS
NON-REMOVABLE NON-VOL. MEMORY INTERFACE
740
REMOVABLE NON-VOL. MEMORY INTERFACE
750
USER INPUT INTERFACE
760
NETWORK INTERFACE
770
MONITOR
791
PRINTER
796
SPEAKERS
797
741
751
755
752
756
761
MOUSE
KEYBOARD
762
LAN
771
772
MODEM
WAN
773
REMOTE COMPUTER
780
781
710
OPERATING SYSTEM 744
APPLICATION PROGRAMS 745
OTHER PROGRAM MODULES 746
PROGRAM DATA 747
REMOTE APPLICATION PROGRAMS 785

Fig. 7

SECURITY SYSTEMS AND METHODS TO REDUCE DATA LEAKS IN ENTERPRISE NETWORKS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority to and the benefit under 35 U.S.C. §119(e) of U.S. Provisional Patent Application No. 61/384,475, filed 20 Sep. 2010, which is incorporated herein by reference in its entirety as if fully set forth below.

GOVERNMENT LICENSE RIGHTS

This invention was made with Government support under Agreement No. CNS-0916732, awarded by the National Science Foundation. The Government has certain rights in this invention.

TECHNICAL FIELD

Various embodiments of the present invention relate to network security and, particularly, to security systems and methods that reduce or prevent data leaks in enterprise networks.

BACKGROUND

Organizations must control where private information spreads and to whom it is accessible; this problem is referred to in the security industry as data loss/leak prevention (DLP). Commercial solutions for DLP are based on scanning content, where the content of traffic flowing outside an organization is compared with patterns of sensitive data (e.g., nine-digit social security numbers) to identify potentially private information. These solutions impose high overhead and are easily evaded, such as by simply encrypting data so that private information is unrecognizable.

Research solutions to the DLP problem require rewriting applications or running custom operating systems, which cause difficulties in deployment for most enterprise environments. These solutions also typically attempt to prevent data loss from a single host, and not across a network, making it challenging to implement a data loss prevention policy for a network of devices.

SUMMARY

There is a pressing need for security systems and methods to reduce or comprehensively prevent the loss of sensitive or confidential data and assets from organizations, even in the face of determined and well-equipped adversaries. Preferably, such security systems and methods must not be easily evaded, for example, by transforming or encrypting sensitive data prior to an attempted leak event. Existing data loss/leak prevention (DLP) systems are overwhelmingly content-based, implying that they can be easily defeated or circumvented through relatively simple and accessible tools. Consequently, various embodiments of this invention are directed towards content-agnostic data loss prevention systems and methods, which are significantly harder to evade, and in addition impose far less overhead than content-based systems.

An exemplary embodiment of such a content-agnostic security system can comprise a labeling system and an enforcement system. Generally, the labeling system can manage security labels for the various sensitive resources or assets within an organization, such as files, processes, memory pages, or database records. Labels have policies (known as capabilities) associated with them that restrict the flow of information from labeled resources. The enforcement system can then control information flows between resources based on the labels and their associated policies.

An exemplary label can comprise a set of taints, where each taint can comprise an identification number, a secrecy bit, and an integrity bit. Each taints can have a capability associated with it that specifies the subset of enterprise users who have permissions to interact with a resource that carries the taint in its label. When the secrecy bit of a taint is set, the associated resource can be deemed secret with respect to that taint, and the security system can control flows of information from the resource to maintain the secrecy of the associated resource conformant to the taint's policy. Similarly, when the integrity bit of a taint is set, the security system can maintain the integrity of the associated resource by limiting information flows into that resource. Each resource can possess one or more of taints in its label, allowing for sophisticated policies to protect sensitive information from leakage as well as tampering.

The enforcement system can require that, for an information flow to occur from a sending resource to a receiving resource, the enterprise user that owns the receiving resource must possess the capability to set the secrecy bit for every taint for which the sending resource has a set secrecy bit. Accordingly, secret data is not shared with a resource for which the owner does not have the capability to read secret data. Additionally, the creator of a secret resource can design a policy that allows a user U the capability to set the secrecy bit for a certain taint while denying the user the ability to unset the bit. This ensures that once U's receiving resource reads a secret resource, it may not be allowed to leak this sensitive information by writing to an external output device (e.g., a USB drive) that has all secrecy bits unset. Similarly, to preserve integrity, the enforcement system can require that the owner of a resource sending data must have the capability to set the integrity bit for every taint in the sending resource for which the receiving resource has a set integrity bit. If these conditions are not met for an attempted information flow, the security system can block the information flow.

This method of preventing data leaks by strictly controlling where sensitive information can flow using resource labels is referred to in prior art as information flow control. Embodiments of the present invention have improvements and benefits over prior art in this area, some of which are as follows: First, the security system can associate capabilities not with resources themselves, but instead with the users who own the resources. This feature allows for unmodified legacy applications to be secured using labels, by making the users that run these applications responsible for policy and capability management. Second, unlike prior information flow control systems, this security system can propagate taints between resources not just on a single computer, but between resources on a network of computers. Third, labels can be applied not just to processes and files, but also to other resources such as database records, memory pages, network sockets, peripheral devices, or the like, allowing arbitrarily fine granularity in controlling the flow of sensitive information. Fourth, the security system can integrate tightly with an enterprise's existing user directories (e.g., Microsoft Active Directory), allowing enterprise users to easily set and change policies on the resources that they own. Fourth, to ensure that a sensitive resource can be taken out of the enterprise only by an authorized user, the security system can require that the user first unset the secrecy bits from all taints in the resource and, in some embodiments, additionally complete a "proofof-human" challenge, such as a CAPTCHA (Completely Automated Public Turing test to tell Computers and Humans Apart), thereby preventing malicious programs masquerading as an authorized user from leaking sensitive information.

These and other objects, features, and advantages of the security system will become more apparent upon reading the following specification in conjunction with the accompanying drawing figures.

BRIEF DESCRIPTION OF THE FIGURES

FIG. **1** illustrates a security system operating within an enterprise network, according to an exemplary embodiment of the present invention.

FIG. **2** illustrates a diagram of a typical label of the security system, according to an exemplary embodiment of the present invention.

FIG. **3** illustrates a typical capability setting for an exemplary taint, according to an exemplary embodiment of the present invention.

FIG. **4** illustrates a workflow involved in creating a new taint and securely applying the taint to a resource in the enterprise network, according to an exemplary embodiment of the present invention.

FIG. **5** illustrates information flow between hosts, according to an exemplary embodiment of the present invention.

FIG. **6** illustrates the security system being designed to protect a set of sensitive database records accessible through a web-based application, according to an exemplary embodiment of the present invention.

FIG. **7** illustrates an architecture of an exemplary host in the network to which the security system applies, according to an exemplary embodiment of the present invention.

DETAILED DESCRIPTION

To facilitate an understanding of the principles and features of the invention, various illustrative embodiments are explained below. In particular, the invention is described in the context of being a security system for reducing data leaks in an enterprise networks. Embodiments of the invention, however, need not be limited to protecting an organization against data leaks. Rather, various embodiments of the invention can be used to manage data permissions within an organizational network, to enable comprehensive tracking and auditing of sensitive data access and use, to protect sensitive data accessed from outside an enterprise network through a potentially untrusted web-based application, and can be used in networks other than enterprise networks.

The components described hereinafter as making up various elements of the invention are intended to be illustrative and not restrictive. Many suitable components that can perform the same or similar functions as components described herein are intended to be embraced within the scope of the invention. Such other components not described herein can include, but are not limited to, similar or analogous components developed after development of the invention.

Various embodiments of the present invention are security systems to reduce data leaks in enterprise networks. An exemplary embodiment of the security system can enforce information flow control across a network for legacy applications. The security system can enable users, such as regular users or administrators of an enterprise, to associate labels with various resources of an enterprise network. Such resources can comprise, for example, files, processes, or database records. Labels can be associated with policies, which can place restrictions on communication to or from resources with a particular label. A labeler module on each host within the network can use the label to determine what communication can take place between labeled resources on the host. When a first resource (e.g., a process) attempts to communicate across the network with a second resource on a different host, the security system can track the flow of information over the network using labels associated with network traffic. The labels can be used to enforce information flow policies, such as on an intermediate network device (e.g., a network enforcer) or on the host that is the intended recipient of the traffic. By enabling information flow control between networked hosts, the security system can also operate in networks with heterogeneous devices and operating systems.

An exemplary embodiment of the security system separates control operations (e.g., determining whether data may be forwarded) from data operations (e.g., forwarding data and associated labels). As a result, embodiments of the present invention provide various benefits over other information flow control systems. For example, the security system can be uniquely able to perform information flow control for unmodified legacy applications in heterogeneous environments due to its novel capability system, which can allow enterprise users to control secrecy and integrity capabilities for their own data. The security system can perform information flow control across a network of hosts running commodity operating systems and unmodified applications, where prior research required all hosts to run a specialized operating system. The security system can also be simple and easily manageable, in that users can specify information flow policies for their own data, which policies can be centrally managed.

A particular exemplary embodiment of the security system operates in the context of web-based applications that are used to access sensitive database records by users external to the enterprise network. In this embodiment, when a user external to the enterprise network requests his or her sensitive database records, the security system can use information flow control to propagate the label on the user's database records across processing or transformation applied on the data by a potentially untrusted or vulnerable web application. The capability on the label can specify that the information flow outside the enterprise is permitted only to the user who owns the label, identified using his or her enterprise authentication credentials. Thus, to retrieve this data from a location external to the enterprise network, the user merely authenticates himself to the enterprise authentication service, which, in coordination with the network enforcer, can enforce information flow between the web application and the public Internet. This embodiment can prevents hacker or malicious web application components from reading a user's sensitive data and sending it out to an unauthorized Internet location.

Referring now to the figures, in which like reference numerals represent like parts throughout the views, various embodiment of the security system will be described in detail.

Overview of the Security System

FIG. **1** illustrates the security system **100** operating within an enterprise network **10**, according to an exemplary embodiment of the present invention. As shown in FIG. **1**, the security system can operate in an enterprise network comprising a plurality of hosts **50**. An exemplary embodiment of the security system **100** can comprise an enforcement system **110** and a labeling system **120**. The labeling system **120** can manage labels of various resources of the hosts **50**. A capability database **430** (FIG. **4**) can manage the capabilities of various enterprise users with respect to the labels on their resources. The enforcement system **110** can be in communication with the hosts **50** and can control how data transactions are handled at each host **50** and between the hosts **50**, so as to enforce the data labels.

The labeling system **120** can comprise a label repository **128**, one or more labelers **125**, and one or more local label stores **123**. The labeling system **120** can be distributed across the plurality of hosts, such that a labeler **125** of the labeling system **120** operates on each host **50**, and a local label store **123** resides on each host. Each labeler **125** can run independently on its associated host **50** in communication with the local label store **123**, and the labeler **125** can label data on that host in accordance with security policies and user instructions. In an exemplary embodiment, the local label store **123** is an in-memory structure that is buffered on disk and maintains the labels of some or all active and persistent resources on the host **50**, such as running processes and files. The local label store **123** can exist to speed up label-related operations on hosts **50** by caching labels of active or persistent resources.

The label repository **128** can be located at a central location and can be in communication with the various labelers **125**. For example, the label repository **128** can be a computing device distinct from the various hosts **50**. The labelers **125** can periodically, or on demand, push updated labels from the local label stores **123** to the label repository **128**. As a result, the label repository **128** can maintain a list of labels for resources throughout the network **10**.

In addition to storing labels of resources on various hosts **50** in the enterprise network **10**, the labeling system **120** can also be responsible for storing capabilities associated with labels through the capability database **430**, including, but not limited to, the various types of permissions enterprise users may have with respect to the taints carried by each label. The capability database **430** of the labeling system **120** will be explained in more detail in a later section.

Through the labeling system **120**, the security system **100** can track and control the propagation of labels. Users of the security system **100** can apply labels to one or a plurality of resources in the enterprise network **10**. Each resource to which a label is applied can be, for example, a file or a process within the network **10**. As the resources interact with each other within a single host **50**, the labeler **125** on host **50** can directly mediate this interaction and enforce information flow checks using a host enforcer **115**. If, however, resources on two networked hosts interact, the labeler **125** can use the help of the label repository **128** in order to transfer the label of the sending resource to the receiving resource, so as to enable enforcement to happen at a network location (e.g., at the switch) or at the receiving host enforcer **115**.

The flow of information generally occurs from a first resource to a second, receiving resource. "Information flow" refers to how data is transmitted from between resources. For example, when a process writes to a file, then data flows from the process to the file. However, when a process reads from a file, then data flows from the file to the process. One of skill in the art will recognize that data may be transmitted, and therefore "flow," between resources in various manners, and that the above examples are provided for illustrative purposes only.

In an exemplary embodiment of the security system **100**, the host **50** of the receiving resource can initiate an information flow check to ensure that the flow of information is permissible. For example, if information in a data transaction flows from a resource P to a resource Q on a single host **50** (e.g., a process writes to a file), the labeler **125** on that host can retrieve the labels for both P and Q before initiating information flow control checks. If P and Q are on different hosts in the network **10** (e.g., a process sends data to a remote server), P's host can automatically push P's label to the label repository **128**. Q's host **50** can automatically retrieve P's label from the label repository **128** and then perform any necessary information flow control checks. If the security system **100** determines that the flow is impermissible, then the interactions between the sending resource and the receiving resource can be blocked by the security system **100**.

In some embodiments, P's host **50** can avoid pushing P's label to the label repository **128**, and instead can directly attach the P's label to the network packets that are sent from P's host **50** to Q's host **50**, usually as an optional field in the Internet Protocol "IP OPTIONS" header.

The enforcement system **110** can perform information flow checks. The enforcement system **110** can comprise a network enforcer **118** and, in some embodiments, a plurality of host enforcers **115**. Each host enforcer **115** can reside on a host **50**. In some embodiments, the host enforcer **115** can be integrated into an operating system, such as in the kernel, of the host **50** on which it resides. The host enforcer **115** reduces information leaks that may occur at the host **50**. For example, and not limitation, the host enforcer **115** may block an attempt by a process to write the contents of a confidential file to a removable drive. For each transaction within a single host where the labels of the sender resource P and the receiver resource Q differ, the labeler **125** of the host **50** can query the host enforcer **115** to decide whether an information flow is permitted.

The network enforcer **118** can control the propagation of information from inside the network **10** to outside the network **10**. In this case, the permissibility of information flow can be based on the sender's label and on network flow attributes. For example, the network enforcer **118** can prevent traffic flows that may contain secret information, as indicated the by the traffic's label, from reaching insecure networks (e.g., an open wireless network, or the outside Internet).

Structure of Taints and Labels

FIG. **2** illustrates a diagram of a typical label **200** of the security system **100**, according to an exemplary embodiment of the present invention. As shown in FIG. **2**, each label can comprise one or more taints **210**, where each taint relates to a quality of a resource to which the associated label **200** is applied.

In some exemplary embodiments, a taint **210** can be represented as an integer, such as a 64-bit integer. A taint can comprise an identification **250** and a value for each of one or more characteristics. Each characteristic can have at least two possible states, where one of such states is applicable at a given time. For example, and not limitation, a characteristic can be active or inactive, true or false, on or off, set or unset, or 1 or 0. Because a characteristic belongs to the taint **210** of which it is a part, it will be understood that references to a taint **210** being in a particular state (e.g., "a secret taint," "an active taint") throughout this disclosure indicate that a characteristic of the taint **210** is in such particular state.

The characteristics of a taint can include, for example, a secrecy characteristic **220** and an integrity characteristic **230**. Each characteristic can be represented in the taint **210** by a Boolean variable, which can be set (i.e., set to "true") or not set (i.e., set to "false"), to indicate whether the characteristic applies to the associated taint **210**. For example, and not limitation, a first bit of the taint **210** can represent a secrecy characteristic **220**, a second bit can represent an integrity characteristic **230**, and the remaining portion of the taint **210** can be an identification **250** of the quality indicated by the taint **210**.

In some exemplary embodiments of the security system **100**, a particular taint **210** with no characteristics in the set state serves no operational purpose within a label **200**. In these exemplary embodiments, if such a taint **210** were removed from the label **200**, the effect of the label **200** on its associated resource would be unchanged. Accordingly, throughout this disclosure, references to a label **200** having a particular taint **210** that is unset with respect to some characteristic may include labels **200** lacking the particular taint **210** in question. When a taint **210** is not present, such taint **210** can be deemed to be unset with respect to all characteristics.

If a characteristic of a taint **210** is set, then the resource to which the label **200** applies can require an information flow check when communicating with other resources, so as to insure that the data of that resource is not shared with resources without adequate capabilities. Generally, in an exemplary embodiment, the security system **100** can prevent information flows from resource P to resource Q, if resource P is labeled with a taint **210** having a set secrecy characteristic **220**, where resource Q does not have the same taint with a set secrecy characteristic **220**. This protects any secret confidential data in resource P from being transferred into resource Q, when Q lacks the same secrecy status. The opposite can be true for the integrity characteristic **230**. An information flow can be blocked when the sending resource lacks a set integrity characteristic **230** in a taint for which the receiving resource has a set integrity characteristic **230**, thus protecting the integrity of the receiving resource. In some instances where the taint's capability permits, which will be explained in more detail below, the security system **100** can automatically raise the secrecy (i.e., by setting the secrecy characteristic for the applicable taint) or raise the integrity (i.e., by setting the integrity for the applicable taint **210**) of the receiving resource, so as to enable the information flow to proceed.

For illustrative purposes, suppose S_p denotes the set of taints in the label **200** of a resource P for which the secrecy characteristic **220** is set, and suppose I_p denotes the set of taints of the same label **200** that have the integrity bit set. If any secrecy or integrity characteristic **220** or **230** of a label **200** is set, the labeled resource can require an information flow check before each attempted communication with another resource is allowed. In some exemplary embodiments, the security system **100** can allow information to flow from P to Q only if:

$S_P \subseteq S_Q$ (i.e., S_P is a subset of S_Q); and

$I_Q \subseteq I_P$ (i.e., I_Q is a subset of I_P).

The rule requiring that S_P be a subset of S_Q is referred to herein as the secrecy rule. The rule requiring that I_Q be a subset of I_P is referred to herein as the integrity rule. It will be understood that, although some exemplary embodiment of the security system **100** require these rules to be met to permit an information flow, other exemplary embodiments can enforce a different set of rules.

Taints, which can make up the labels, can be initially set up by users of the security system **100**. Whether the security system **100** allows a user to create a new taint or modify an existing label **200** with a specific taint can depend on the assigned capabilities of the user with respect to the taint **210** in question.

Taint Capabilities

FIG. **3** illustrates a typical capability setting **310** for an exemplary taint, according to an exemplary embodiment of the present invention. The taint capability **310** can be maintained for centrally by the capability database **430**. The host enforcer **115** and network enforcer **118** can query the capability database **430** when they encounter an information flow between two resources where at least one resource's label possesses the taint **210** in question. The taint capability **310** can comprise the taint identification **250**, a taint mnemonic **320** that is used by lay enterprise users to denote taint identification **250**, and a capability table **330** that denotes the capabilities of enterprise users with respect to the taint **210**.

The taint mnemonic **320** can be a string or phrase that is assigned to the taint **210** by the user that originally creates the taint, preferably chosen so that it is easy to memorize. For example, and not limitation, if the taint **210** is used to protect sensitive data pertaining to employee salary reports, the user that creates the taint can assign the taint mnemonic **320** as "Salary Reports."

The capability table **330** can be a dynamic table that denotes the capability of each enterprise user in two cases: (1) when a resource owned by the user possesses the taint **210** in its own label and attempts to interact with other resources, or (2) when a resource owned by the user interacts with another resource that possesses the taint **210** in its label. The capability table **330** can include, but is not limited to, a list of usernames **331** and their capabilities **332**-**337** with respect to the taint identification **210**.

Each user of the network can have, but is not limited to, zero, one, or more of various capabilities with respect to each taint **210**. For each taint, available capabilities can include the following:

1. Capability to set the secrecy characteristic (s+ **332**);
2. Capability to unset the secrecy characteristic (s− **333**);
3. Capability to set the integrity characteristic (i+ **334**);
4. Capability to unset the integrity characteristic (i− **335**);
5. Capability to add users who can make modifications to the taint capability **310** (o+ **336**); and
6. Capability to remove users who can make modifications to the taint capability **310** (o− **337**).

The user who creates a particular taint **210** can automatically have all six capabilities with respect to the taint **210**. When a new user is added to those who can manage the taint **210**, the new user can automatically be granted a subset of the capabilities. For example, and not limitation, let enterprise user Alice be a user who creates a particular taint **210**; consequently, she can receive all capabilities **332**-**337** for the taint **210**, denoted by check marks (✓) in the capability table **330** corresponding to Alice's row. Because Alice possesses the o+ capability, she may add a user, Bob, to the capability table, allowing him only the capability for s+ and i−, denying him s−, i+, o+, and o−, as denoted by cross marks (x) in the capability table **330** corresponding to Bob's row.

In addition, the capability table **330** can also have a wildcard user entry **340** that can be used to denote permissions toward users not explicitly named in the capability table **330**. The wildcard capability setting can be used by the owner(s) of the taint **210** to automatically set permissions for other enterprise users. For example, Alice could set the s+ capability alone for the wildcard user to allow other enterprise users to access and read data from a resource that possesses the taint **210**, but deny these users from leaking any sensitive information from the resource after they have read it. The utility of various fields in the capability table **330** will become apparent in the following sections, which discuss host enforcers **115** and network enforcer **118**.

One of skill in the art will recognize that the representations of the capability table **330** is exemplary, and actual implementations may involve analogous or extended representations for storing capabilities of users with respect to taint identification **250**.

Creating and Applying Taints to Resources

FIG. **4** illustrates a workflow involved in creating a new taint and securely applying the taint to a resource in the enterprise network, according to an exemplary embodiment of the present invention. An enterprise user **410** may use an enterprise host **50** to create and apply a taint **210** to a file F **435**, in this workflow. The host **50** may run an operating system that can typically be partitioned into programs running in userspace **420** and kernel space **430**. Within the context of the security system **100**, accesses to the file F **435** can be mediated by the labeler **125**, in coordination with the host enforcer **123** and the capability database **430**.

In an exemplary embodiment of the security system **100**, a user **410** does not have direct access to labels associated with the various resources of the host **50**. To protect a file F **435**, using the security system, the user **410** may be required to use a centralized authentication service and taint management console **445**. Step **1** in protecting file F **435** can be to use a taint management application **425** running in userspace **420** on host **50** to choose a file F **435** to which a taint **210** is to be created and applied. The taint management application **425** can be various programs that can communicate with the authentication service and taint management console **445**. For example, and not limitation, the user **410** can use a web browser for this purpose. Alternatively, the user **410** can use a desktop service to communicate with authentication service and taint management console **445**, which can be invoked by accessing familiar permissions menus, e.g., by "right-clicking" a file and choosing "File Properties."

The taint management application **425** can communicate the user's taint management request on behalf of the user to the authentication service and taint management console **445**, as illustrated in Step **2**. The request can comprise, without limitation, the following information: (1) the credentials (e.g., a login username, password, and optionally a CAPTCHA test to distinguish automated requests); (2) the identification of the file F **435** or any other resource for which the user wishes to manage labels **200** or taints **210**; (3) the type of request, which can be, but is not limited to, one of TAINT_CREATE, TAINT_MODIFY, or TAINT_MANAGE.

The authentication service and taint management console **445** can be a centralized service that can be in communication with a plurality of hosts **50** in the enterprise, the capability database **430** (in order to create and manage capabilities on taints), and an enterprise-wide user directory service, for example, Microsoft Active Directory, OpenLDAP (Lightweight Directory Access Protocol), or Network Information Services (NIS). The authentication service and taint management console **445** can also provide a detailed visual display for each authenticated user **410** that allows him or her to view, create, manage, and modify one or more of the taints owned by the user **410**. After the authentication service and taint management console **445** authenticates the user **410**, it can accept the remainder of the user's request, which may include an identifier to a resource in the enterprise and a request type. The identifier to the resource can include the host identifier where the resource is located, the access path for the resource, and the type of resource (e.g., file, process, memory page, database record, etc.). For illustration, FIG. **4** illustrates an example in which the resource chosen by the user **410** is a regular file, F **435**, located on the user's own host **50**.

The user **410** can issue various types of requests. The TAINT_CREATE request may be used by the user **410** to create a new taint **210** with default capabilities, which defaults can place the user **410** as owner of the newly created taint **210** with full capabilities, and no capabilities for other users. This request can carry additional parameters including, but not limited to, the taint mnemonic **320** and a capability table **330**. The TAINT_MODIFY request can be used to modify the capabilities of an existing taint that has user **410** listed as an owner (i.e., the o+ and o− capabilities). This request can carry additional parameters that specify the type of modification requested, which may include changing the taint mnemonic **320**, adding or removing users to the capability table **330**, or changing specific capabilities for one or more users in the capability table **330**. The TAINT_MANAGE request can be used for additional commands pertaining to taints, including, but not limited to:

1. Adding the taint to a resource's label: This type of request can add the requested taint to a specified resource's label, provided the user **410** has the required capabilities to perform this action.
2. Adjusting capabilities of taints in a label: If the taint is already present to the specified resource's label, this type of request can set or unset the secrecy or integrity characteristic for that taint, provided the user **410** has the required capabilities as per the capability database **430**.
3. Removing a taint from a resource's label: This type of request can remove a taint **210** from a specified resource's label **200**, which may imply adjusting capabilities of the selected taint **210** by unsetting both the secrecy and integrity characteristics **220** and **230** from the taint **210** in the specified resource's label **200**.

In Step **3** of FIG. **4**, the authentication service and taint management console **445** can verify that the specific request issued by the user **410** satisfies the capabilities assigned to the user **410**. In Step **4**, the capability database **430** can repackage the request and communicate with the labeler **125** on the host **50** where the specified resource, file F **435**, is located. In Step **5**, the labeler **125** on the host **50** can locate the resource, file F **435**, and perform the requested operation on the specified taint **210** on file F's label **200**. Depending on the outcome of this action, the labeler **125** can inform the capability database **430** and the authentication service and management console **445** about the success status of the request. In Step **6**, the authentication service and taint management console **445** can communicate the success or failure of the user's request back to the user through the taint management application **425**.

Enforcement of Labels with Information Flow Checks

FIG. **5** illustrates an example of checking information flow within a single host **50**, according to an exemplary embodiment of the present invention. It will be understood that this example is provided for illustrative purposes only and does not restrict the scope of the invention. As shown in FIG. **4**, file F and process P reside on the host **50**. Process P attempts to read secret File F, which would result in a flow of information from file F to process P.

File F is a secret file (i.e., is labeled with a taint having a set secrecy characteristic). When process P attempts to read F, the labeler **125** retrieves the labels for file F and process P from the local label store **123**. The labeler **125** then queries the host enforcer **115** with the labels **200** of F and P to determine whether information from F to P is permissible. The host enforcer **115** retrieves the capabilities of the users that own F and P for all taints in the labels of F and P from the capability database **430**, and the hose enforcer **115** then determines whether the attempted information flow would cause a violation of the secrecy rule, the integrity rule, or another information flow rule.

FIG. **5** illustrates an example of checking information flow between two resources on different hosts **50** across the network **10**, according to an exemplary embodiment of the present invention. As shown in FIG. **5**, suppose a malicious process P on a first host **50** attempts to exploit a trusted server process Q on a second host **50**. Because the attempted information flow requires P's data to be transmitted over the network **10**, the labeler **125** on the first host **50** pushes P's current label **200** to the label repository **128**, which can be at a location accessible to the network enforcer **118** and the labeler **125** of the second host **50**. The network enforcer **118** can check whether the attributes of the information flow and of P's label **200** permit the attempted information flow to occur. If the network enforcer **118** allows the information flow to reach the second host **50**, the labeler **125** of the second host **50** can retrieve P's label **200** from the label repository **128**. From this point forward, the security system's operations can be the same or similar to those that would occur from an information flow attempt isolated to a single host **50**. The second host's labeler **125** can invoke its host enforcer **115** to perform the information flow check using the respective labels **200** of P and Q. The host enforce **115** can complete this check after retrieving the appropriate user capabilities from the capability database **430**.

Preventing Data Leaks

The security system can prevent data leaks using information flow control. Sensitive data that is to be protected from leaks can be associated with a taint **210**, T. The user that applies the taint T to the sensitive data may ensure that none but a trusted set of enterprise users are granted the s+ capability on the taint T. Thus, when an unauthorized user not in the set of trusted users attempt to access a file protected with taint T, the host enforcers **115** on the applicable hosts **50** can determine, using the capability database **430**, that the information flow to the unauthorized user's program constitutes an unpermitted information flow, and can therefore prevent the operation from taking place.

Now assume that one of the users in the trusted set of users who are granted the s+ capability on taint T is malicious and wishes to leak the sensitive information outside the enterprise network. Such cases would include, for example: (1) the user is benign but is accidentally running a malicious program which attempts to leak the data, or (2) the user is benign, but a service that runs under the user's capability is under the control of a hacker external to the enterprise. Because the user is granted s+, his programs are able to read the sensitive data, and even make copies, some of which may even be encrypted. However, the labeler **125** on the malicious user's host **50** can ensure that all copies of the sensitive data will continue to carry the taint T.

Now suppose the malicious user attempts to copy an encrypted version of the sensitive data to a removable disk drive. The host enforcer **115** on host **50** cam always assign immutable empty labels **200**, which carry no taints **210**, to each output device that represents a potential data leak. Thus, the host enforcer **115** can understand that writes of sensitive-labeled data to unauthorized output devices, including, for example, removable disk drives, printers, secondary network cards, Bluetooth, and infrared, constitute a violation of information flow control rules, because the label **200** of the output device cannot carry a secret taint **210**, even if the user possesses the s+ capability. Thus, the host enforcer **115** can detect a potential data leak and stop the requested transfer from taking place. The malicious user may also be unable to leak sensitive data over the network **10** (e.g., over an encrypted connection to a remote Internet server) because the network data that he sends out can be identified as carrying sensitive content by the network enforcer **118** using the label repository **128**, and can therefore be blocked from leaving the network **10**. Because the owner of the taint T only granted the malicious user the s+ capability and not the s− capability, the user may be unable to remove the taint T from any of his files that contain sensitive content.

Preventing Data Leaks in Web-Based Applications

An exemplary embodiment of the security system **100** can be used to prevent data leaks in web-based applications that are used to access sensitive data stored in files or database records. Web-based applications may be used by enterprise users to access their sensitive data stored in internal enterprise servers from outside the enterprise. Unfortunately, web-based applications today are a primary vector of data leaks from enterprises and are regularly exploited to leak sensitive database records from organizations. Embodiments of the security system **100** can defend against breaches that exploit web application vulnerabilities while permitting legitimate enterprise users to seamlessly access their sensitive data from outside the enterprise.

FIG. **6** illustrates an exemplary embodiment of the security system **100** designed to protect a set of sensitive database records accessible through a web-based application **620**. It will be understood that various other implementations of the security system **100** may also be used to prevent data leaks through web applications **620**, and the implementation provided in FIG. **6** is for illustrative purposes only.

A sensitive database **610** on a host **50** can contain one or more records that are sensitive, with an enterprise user's sensitive data occupying one or more rows of the database **610**. For example, and not limitation, the database **610** can include three columns: a user name, a secret (e.g., an account balance), and a taint **210** that is attached to each sensitive record. The database **610** may be accessible to enterprise users from outside the enterprise network **10** through an untrusted web application **620**. The web application may be susceptible to compromise by external hackers, or the web application **620** itself may be malicious and attempt to send data it reads from the database **610** to unauthorized destinations outside the network **10**. The database **610** and untrusted web application **620** can run on hosts **50** equipped with the labeler **125** and host enforcer **115**, positioned within the enterprise network **10** behind the network enforcer **110** and an authentication service and taint management console **445**.

This exemplary embodiment of the security system **100** can allow legitimate users to retrieve their secret database records while disallowing hackers, or a malicious web application components, from leaking data. In Step **1**, a legitimate user may connect to the web application's Uniform Resource Locator (URL) in order to access the user's secret data. Prior to reaching the web application **620**, the user can be redirected to the authentication service and taint management console **445** in Step **2**, where the user must authenticate himself by presenting his enterprise credentials. Once authenticated, the user can be redirected to the untrusted web application **620** in Step **3**, where the user man request that the web application **620** retrieve his secret account balance from the database **610**. In step **4**, the web application **620** may issue a retrieve request on behalf of the user for the user's database entry. In Step **5**, the requested database record may be released by the database **610** after applying an applicable taint **210** to the data prior to release. This taint **210** can be compared by the host enforcer **110**, on either the database server host **50** or the web application server host **50**, to ensure that the requesting user has the requisite capability to view the record (e.g., the s+ capability). After receiving the database record, the web application **620** may forward a response to the user through the network enforcer **110**. At this stage, in Step **6**, the network enforcer **118** can compare the taint **210** on the outgoing data flow with the list of users that are logged in, utilizing the authentication service and taint management console **445** as needed. This step may be crucial to decide whether the user who requested the data has the requisite capability to declassify the data such that it can be sent outside the enterprise network **10** (e.g., the s− capability). After the network enforcer **118** confirms that the tainted network flow is destined to the web session of an authenticated user with the appropriate capability with respect to the taint **210**, the network enforcer **118** can automatically declassify the taint **210** to permit the data to leave the enterprise network **10**.

Resultantly, the security system **100** can prevent data leaks even if the untrusted web application **620** is compromised in one of many potentially unknown ways. Even if an attacker has complete control over the web application **620** and can read any database record from the database **610** without hindrance, the attacker may be blocked from exporting sensitive data outside the network **10**, because the authentication service and taint management console **445** can find that the attacker is attempting to access sensitive information carrying a taint **210** on which the attacker does not have the s− capability.

Improvements Over Prior Art in Information Flow Control

Some aspects of the present invention are related to prior art in information flow control. Specifically, in "A Decentralized Model for Information Flow Control" published in the 1997 Symposium on Operating Systems Principles by Andrew C. Myers and Barbara Liskov, the authors propose a programmatic model to restrict the flow of information between components of applications such that an untrusted application cannot leak it. In "Information Flow Control for Standard OS Abstractions" published in the 2007 Symposium on Operating Systems Principles, Maxwell Krohn et al. propose an information flow control scheme that works on commodity operating systems.

Various embodiments of the present invention include improvements over prior art that can make the present security system **100** more effective, convenient, functional, practical, or cost-effective than the prior art. First, the present invention can perform information flow control for unmodified, legacy applications, whereas the prior art requires applications to be rewritten to take advantage of the information flow control system. In the prior art, applications are required to manage labels and capabilities programmatically and in a decentralized fashion. This approach proves difficult or impossible in most organizations where applications are proprietary and run on commodity operating systems, and modifying source code for such applications is not possible. Embodiments of the present invention need not require application modification, and can work on commodity operating systems. Using a simple and lightweight operating system update that installs the labeler **125**, label store **123**, and host enforcer **115**, the security system **100** can track information flow for unmodified applications by offloading the work of setting and managing policies on labels **200** to the users of the enterprise network **10** through the centralized authentication service and taint management console **445** and the capability database **430**.

A second advantage of various embodiments of the present invention is the ability to perform information flow tracking over hosts **50** in a large, globally distributed enterprise network **10**, whereas previous inventions in information flow control are limited to a single host or, at the most, to a small number of hosts. In the present invention, the host labelers **125** can coordinate with the label repository **128** to transfer labels **200** between processes communicating over the network **10**. A globally distributed enterprise network **10** may have multiple globally distributed label repositories **128** to ensure information flow tracking at a global scale. The label communication scheme works on the existing IP protocol and thus requires no reconfiguration of traffic filtering rules in the enterprise network **10**.

A third and major improvement of some embodiments of the present invention is an improvement to the rules of information flow control used in prior art, and improvement that can result in minimal inconvenience for enterprise users when dealing with resources whose labels **200** have one or more taints **210** with the secrecy characteristic **220** set. Typically, in enterprise networks **10**, sensitive information is broadly accessible to enterprise employees and users, and the key need for enterprises is not to prevent employees from viewing sensitive data but to prevent them from exfiltrating such data outside the enterprise network confines. In conventional information flow control policy schemes, if a resource P with no taints in its label attempts to read information from a resource Q with one secrecy taint **210**, the resource P first has to apply the taint **210** to its own label **200** to raise its own secrecy level, provided the user that owns P possesses the s+ capability on the taint **210**; only then can P attempt reading from the resource Q. If the present invention followed standard rules of information flow control, the user that owns P would have to manually apply the taint **210** to P each time P accessed a sensitive resource, even if the user possessed the s+ capability on the taint **210**.

To reduce user intervention and to allow newly created processes to read secret files without alerts and warning messages, the security system **100** can modify the conventional rules for information flow control. Specifically, in some embodiments of the security system **100**, the labeler **125** can automatically allow information flows that only raise a resource's secrecy (or integrity), provided that the user owning the resource has the s+ capability to the raise the resource's secrecy. Thus, within the enterprise network perimeter protected by the security system **100**, users can access sensitive resources as normal, using various programs of their choice, with information flow tracking being transparent to them and their applications.

This novel functionality can be implemented using the wildcard capability **340** in the capability table for a taint **210**. At taint creation, the user that creates a taint **210** can choose to set a default wildcard policy for other enterprise users, which can grants other users the s+ capability without granting them the s− capability. This policy can ensure that users other than the creator of the taint **210** can read sensitive resources labeled with the taint **210** but may not remove the taint **210**, so as to leak information outside the network **10**.

In contrast, lowering secrecy or integrity, such as by unsetting a characteristic from a taint **210**, can potentially cause data leaks, and may thus require explicit user action. Removing the secrecy characteristic **220** on a taint **210** for a resource is known as declassification. In some embodiments of the security system **100**, declassification may always require user intervention, to confirm that the user wished to declassify a particular resource. In many cases, even if the user who requests declassification possesses the s− capability for the taint **210** in question, the authentication service and taint management console **445** can require the user to solve a CAPTCHA to ensure that the declassification is not requested by an automated malicious program masquerading as the user.

Implementation: Overview

One or more aspects of the security system **100** and related methods can be embodied, in whole or in part, in a computing device **700**. For example, one or more hosts **50** can be computing devices, and the network enforcer **118** can be a computing device **700** or a portion thereof. FIG. **7** illustrates an example of a suitable computing device **700** that can be used in the network **10** in which the security system **100** operates, according to an exemplary embodiment of the present invention.

Although specific components of a computing device **700** are illustrated in FIG. **7**, the depiction of these components in lieu of others does not limit the scope of the invention. Rather, various types of computing devices **700** can be used to implement embodiments of the security system **100**. Exemplary embodiments of the security system **100** can be operational with numerous other general purpose or special purpose computing system environments or configurations. Examples of well-known computing systems, environments, and/or configurations that can be suitable for use with the invention include, but are not limited to, personal computers, server computers, hand-held or laptop devices, multiprocessor systems, microprocessor-based systems, set top boxes, programmable consumer electronics, network PCs, minicomputers, mainframe computers, distributed computing environments that include any of the above systems or devices, and the like.

Exemplary embodiments of the security system **100** can be described in a general context of computer-executable instructions, such as one or more applications or program modules, stored on a computer-readable medium and executed by a computer processing unit. Generally, program modules can include routines, programs, objects, components, or data structures that perform particular tasks or implement particular abstract data types.

With reference to FIG. **7**, components of the computing device **700** can comprise, without limitation, a processing unit **720** and a system memory **730**. A system bus **721** can couple various system components including the system memory **730** to the processing unit **720**.

The computing device **700** can include a variety of computer readable media. Computer-readable media can be any available media that can be accessed by the computing device **700**, including both volatile and nonvolatile, removable and non-removable media. For example, and not limitation, computer-readable media can comprise computer storage media and communication media. Computer storage media can include, but are not limited to, RAM, ROM, EEPROM, flash memory or other memory technology, CD-ROM, digital versatile disks (DVD) or other optical disk storage, magnetic cassettes, magnetic tape, magnetic disk storage or other magnetic storage devices, or any other medium which can be used to store data accessible by the computing device **700**. For example, and not limitation, communication media can include wired media such as a wired network or direct-wired connection, and wireless media such as acoustic, RF, infrared and other wireless media. Combinations of any of the above can also be included within the scope of computer readable media.

The system memory **730** can comprise computer storage media in the form of volatile or nonvolatile memory such as read only memory (ROM) **731** and random access memory (RAM) **732**. A basic input/output system **733** (BIOS), containing the basic routines that help to transfer information between elements within the computing device **700**, such as during start-up, can typically be stored in the ROM **731**. The RAM **732** typically contains data and/or program modules that are immediately accessible to and/or presently in operation by the processing unit **720**. For example, and not limitation, FIG. **7** illustrates operating system **734**, application programs **735**, other program modules **736**, and program data **737**.

The computing device **700** can also include other removable or non-removable, volatile or nonvolatile computer storage media. By way of example only, FIG. **7** illustrates a hard disk drive **741** that can read from or write to non-removable, nonvolatile magnetic media, a magnetic disk drive **751** for reading or writing to a nonvolatile magnetic disk **752**, and an optical disk drive **755** for reading or writing to a nonvolatile optical disk **756**, such as a CD ROM or other optical media. Other computer storage media that can be used in the exemplary operating environment can include magnetic tape cassettes, flash memory cards, digital versatile disks, digital video tape, solid state RAM, solid state ROM, and the like. The hard disk drive **741** can be connected to the system bus **721** through a non-removable memory interface such as interface **740**, and magnetic disk drive **751** and optical disk drive **755** are typically connected to the system bus **721** by a removable memory interface, such as interface **750**.

The drives and their associated computer storage media discussed above and illustrated in FIG. **7** can provide storage of computer readable instructions, data structures, program modules and other data for the computing device **700**. For example, hard disk drive **741** is illustrated as storing an operating system **744**, application programs **745**, other program modules **746**, and program data **747**. These components can either be the same as or different from operating system **734**, application programs **735**, other program modules **736**, and program data **737**.

A web browser application program **735**, or web client, can be stored on the hard disk drive **741** or other storage media. The web client **735** can request and render web pages, such as those written in Hypertext Markup Language ("HTML"), in another markup language, or in a scripting language.

A user of the computing device **700** can enter commands and information into the computing device **700** through input devices such as a keyboard **762** and pointing device **761**, commonly referred to as a mouse, trackball, or touch pad. Other input devices (not shown) can include a microphone, joystick, game pad, satellite dish, scanner, electronic white board, or the like. These and other input devices are often connected to the processing unit **720** through a user input interface **760** coupled to the system bus **721**, but can be connected by other interface and bus structures, such as a parallel port, game port, or a universal serial bus (USB). A monitor **791** or other type of display device can also be connected to the system bus **721** via an interface, such as a video interface **790**. In addition to the monitor, the computing device **700** can also include other peripheral output devices such as speakers **797** and a printer **796**. These can be connected through an output peripheral interface **795**.

The computing device **700** can operate in a networked environment, being in communication with one or more remote computers **780**, such as other hosts **50**, over the network **10**. The remote computer **780** can be a personal computer, a server, a router, a network PC, a peer device, or other common network node, and can include many or all of the elements described above relative to the computing device **700**, including a memory storage device **781**.

When used in a LAN networking environment, the computing device **700** can be connected to the LAN **771** through a network interface or adapter **770**. When used in a WAN networking environment, the computing device **700** can include a modem **772** or other means for establishing communications over the WAN **773**, such as the internet. The modem **772**, which can be internal or external, can be connected to the system bus **721** via the user input interface **760** or other appropriate mechanism. In a networked environment, program modules depicted relative to the computing device **700** can be stored in the remote memory storage device. For example, and not limitation, FIG. **7** illustrates remote application programs **785** as residing on memory storage device **781**. It will be appreciated that the network connections shown are exemplary and other means of establishing a communications link between the computers can be used.

The inventors built a prototype of the security system **100**, the details of which are discussed below. It will be understood that the prototype is illustrative of one exemplary embodiment and does not limit the scope of the invention.

Implementation: Host Components

In the prototype security system **100**, the labeler **125**, the label store **123**, and the host enforcer **115** are implemented as an operating system patch for the open source Linux operating system. The labeler **125** is implemented using Linux Security Modules (LSM), which is a framework within the Linux kernel that allows various security models to be added-on without changing core kernel code. LSM provides hooks within system call handlers that can be implemented by a security module. Thus, a third party module can implement mandatory access control for a system call (e.g., read(**2**)) without changing the core implementation of the system call handler (e.g., sys_read). Using LSM hooks, the labeler **125** intercepts all system calls that transfer information between resources on a host **50**. Hooks are used to track information flow for system calls listed in Table 1, which appears below. These are merely exemplary, not limiting, and the security system **100** may track information flow for calls not listed in Table 1 or calls that are added to operating systems in future.

TABLE 1

Syscall Type	Example syscalls
Inter-process Communication	send(2), shmat(2), msgsnd(2), kill(2)
File/device operations	read(2), unlink(2), mknod(2)
Process creation	fork(2), execve(2), clone(2)
Memory operations	mmap(2), mprotect(2)
Kernel configuration	sysctl(2), init_module

In addition to hooking system calls that transfer information, the prototype labeler **125** also monitors access to memory pages. Specifically, where the labels **200** are tracked at the granularity of memory pages, and not at the granularity of a process that consists of several memory pages, system calls are not sufficient to track all flow of information between memory pages. For example, and not limitation, a userspace process may have two memory pages mapped into its virtual address space. Suppose that one of such memory pages has a label **210** attached to it while the other memory page does not. If the process executes an instruction in userspace that moves a byte of data from the labeled memory page to the unlabeled memory page, a system call hook at the kernel will be unable to intercept this information flow.

To intercept this information flow from the kernel without placing any trust in the userspace applications, the labeler **125** is augmented with additional functionality. Specifically, the labeler **125** uses hardware-level write protection on memory pages, which is available on all major processor architectures, to be notified whenever there is a write to a memory page. In the example of two memory pages cited above, the labeler **125**, at the time of allocating a memory page and mapping it to a process's virtual address space, sets the write-protection on the page if any other pages in the process's address space carry a label **200**. This step can ensure that whenever an instruction executing in userspace attempts to copy information to the unlabeled memory page, the write protection can raise a fault, which can be trapped by the labeler **125** residing in the kernel. At this point, the labeler **125** inspects the source and destination of the instruction that caused the trap. In case the source originated from a page that had a label **200**, the label **200** is carried over to the write-protected page, and the write protection is removed before allowing the instruction to execute. Otherwise, the write-protect is temporarily removed, the instruction is executed, and the write-protect is re-enabled before returning control back to user-space.

An enterprise administrator installs the labeler **125** module on the operating system of the host **50** when the host is in a known "clean" state (e.g., as might be determined by an audit, virus scanner, or by using a Linux distribution with the pre-loaded labeler for installation). On reboots, the labeler **125** is automatically loaded shortly after initialization (i.e., init) during the boot sequence.

The labeler **125** maintains a label **200** for every resource on the host **50** that is associated with at least one taint **210**. Each taint **210** of a label **200** includes an identification, a secrecy bit, and an integrity bit. A taint **210** is described by the taint identification and its current setting of secrecy and integrity bits. The local labeler **125** does not maintain capabilities of the user that owns the resource, as such capabilities are maintained in the central capability database **130**. For efficiency, the labeler **125** does not create or maintain labels **200** for files and directories that have no taints in their label **200**, instead assigning such resources a "null" label **200**.

The local label store **123** is a partition that is encrypted using a key embedded in the kernel image. The local label store **123** is stored in a partition not readable to user space processes (enforced using LSM checks). On disk, labels **200** are indexed by the inode numbers or process identifications of the resources to which they map. Label **200** reads and writes are buffered using an in-memory cache. At shutdown, labels for files and directories are written to disk, and process labels are discarded. To prevent loss of sensitive labels **200** in the event of a machine crash, the prototype security system **100** use a journaling file system on the label store **123** partition. Labels **200** of a file are written back to the label store **123** before the file's inodes themselves are written to disk. Although not required in every embodiment of the security system **100**, the label store **123** of the prototype security system **100** back up the labels **200** to the label repository **128** periodically.

The labeler **125** enforces information flow control checks using the host enforcer **115**, which is implemented as a kernel patch. Alternatively, the host enforcer **115** can be implemented below the kernel in a hypervisor or on a trusted platform module. The host enforcer **115** executes with the same or higher security and privileges as the labeler **125**. The labeler **125** invokes the host enforcer **115** when it detects information flow between two resources that have incompatible labels **200**. The host enforcer **115** communicates with the capability database **430** to retrieve the appropriate capabilities, but in some instances, the host enforcer **115** can make a decision without querying the capability database **430**. For example, if the sending resource's label **200** cannot be automatically declassified and has one or more secrecy taints **210**, and the destination is a removable drive, the host enforcer **115** denies the information flow without checking the capability database **430**.

The capability database **130** and label repository **128** are hash tables that allow clients to look up values of keys. Both of these services are implemented using Redis, an exemplary high performance key-value store. Redis supports only string keys, but values can be of any type. Keys for the capability database are the taint identifications **250**, and each value is a structure that contains the name for the taint **210** and a list of users and their capabilities over the taint **210**.

Implementation: Network Components

A challenge in enforcing information flow control throughout the network **10** is that a receiving host's enforcer **115** may need to make information flow control decisions without having immediate access to the labels **200** associated with the sending resource. To uniquely associate a sending resource with a label **200**, the sender's labeler **125** can annotate each packet with a resource identification and a version number. The network enforcer **118** or the enforcer **115** on the receiving host **50** can retrieve the sending resource's label **200** using the sender's IP address, resource identification, and version number from the label repository **128**. The resource identification can be unique during a resource's lifetime. Version numbers can increment from zero and indicate the version of the sending process's label **200**. If the sending process's label **200** changes, the sender's labeler **125** can annotate subsequent packets with the incremented version number to indicate to the receiving labeler **125** that the sender's label **200** has changed.

During an information flow check, the receiving labeler **125** can extract the resource identification and version number from the packet header for an incoming flow and can retrieve the sender's label **200** from the label repository **128**. Because the labeler **125** has local access to the current label **200** for the receiving process, the labeler **125** can perform information flow control checks using the host enforcer **115** at the receiving host **50** in the same, or similar manner, that such checks would be performed for an intra-host information flow check.

The network enforcer **118** can typically reside at boundaries between networks of different trust levels, such as at the edge of the enterprise network **10** leading to the Internet, or between wired and wireless network boundaries within the enterprise. The network enforcer **118** can have policies that designate immutable secrecy and integrity taint sets to certain destination prefixes or to specific ports of the network device. For example, and not limitation, a host enforcer **115** of a sending host **50** can designate traffic destined to the Internet as having a particular immutable taint **210**. When a network enforcer **118** sees a new data flow, it can extract the resource identification and version number from the packet header and retrieve the sender's label **200** from the label repository **128**. The network enforcer **118** can then perform information flow control checks to ensure that the attempted information flow is permitted. When the network enforcer **118** sees the immutable taint **210** related to Internet traffic, it can determine whether the sending process had any secrecy taints **210** at all. If the sending process had secrecy taints, the network enforcer **118** can prohibit the attempted information flow.

If a flow passes information flow control checks, the network enforcer **118** can install a rule that allows future packets with the same resource identification and version number back into the network **10** without undergoing checks.

Although the network enforcer **118** may be any of various devices capable of inspecting network traffic and corresponding labels from the label repository **128**, the prototype security system **100** uses a slightly-modified OpenFlow switch implementation, along with a custom NOX controller that communicates with the switch over a secure channel. The controller queries the capability database **130** and the label repository **128** to make information flow decisions and installs rules on the network switch to forward or block flows based on the decisions. The prototype security system **100** uses modified OpenFlow switches to augment flow table entries with label version numbers. When a new flow arrives, the switch forwards the traffic to the controller, and the network enforcer **118** at the controller performs any necessary information flow control checks. If the information flow is permitted, the controller inserts a flow table entry in the switch, and data packets that match this entry are forwarded without further checks. If the version numbers embedded in the data packets change mid-flow, the flow table entry will no longer match, at which point the controller performs a new information flow check on the new version of the sender's label.

Implementation: Security Features

Although the label repository **128** can contain labels from various hosts **50**, a particular labeler **125** can be limited to pushing and manipulating labels **200** in the label repository **128** only for resources that are associated with its host **50**. In some embodiments, labelers **125** can be uniquely identifiable so that the security system **100** can associate each labeler **125** with its host **50**, even as hosts **50** enter and leave the network **10** or change IP addresses. Thus, an administrator may assign a unique private/public key pair to each labeler **125** when the labeler **125** is installed on the corresponding host **50**. The public key can act as an identification for the host **50** and can be used for self-certification. The public key can also be used to generate a session encryption key to encrypt control traffic related to the security system **100**.

When a host **50** enters the network **10** and joins the security system **100**, its labeler **125** can register with a labeler authentication service. The labeler authentication service can associate each host **50** with its host identification, so the public key for a host **50** can be used to prove the labeler's identity and to securely establish an expirable session key for use between the labeler **125** and enterprise services (e.g., label repository **128**, capability database **430**, authentication service and taint management console **445**). The labeler **125** can interact securely with the label repository **128** to register storage for itself as needed and to push and retrieve labels **200** for inter-host communication.

In some cases, a host **50** may have multiple network interfaces, with only one is connected to the enterprise network (i.e., the "primary" interface). In that case, the labeler **125** can determine the primary interface, so as to denote all other interfaces as potential avenues for data leaks. To discover the primary interface, the host labeler **125** can broadcast a message to all configured interfaces and then designate the interface on which it receives a signed response from the labeler authentication service as the primary network interface.

The security system **100** can fix the taints of certain resources, so as to limit the abilities of such resources. For example, at boot time, the host enforcer **115** can build a list of all output devices (except the display device) as potential avenues for information leaks. The host enforcer can then set an immutable label **200** of these devices, so as to prevent tainted resources from writing to these devices. The primary network interface card and the primary hard disk can be excluded from the devices receiving this label **200**. These two devices can instead receive an immutable "master" label **200**. The master label **200** can indicate that send(**2**) and recv(**2**) through these interfaces do not involve information flow checks or label adjustments.

For example, and not limitation, all electronic messages and external drives, such as flash drives, can receive empty immutable labels **200**. Thus, in the attempt of a user to copy a file to a flash drive where the file has any secrecy taints **210**, the user may be unable to raise the secrecy of the flash drive so as to enable the information flow. However, if the user has the capability to lower the secrecy of the file with respect to the applicable taints **210**, then the user can do so, thus enabling the file to written to the flash drive.

As mentioned above, a user who owns a taint **210** may limit which people have the capability of unsetting the secrecy characteristic **220** of that taint **210**. Resultantly, a user may limit which users can transmit data associated with the taint **210** outside of the network **10**.

In short, labels **200** can enable users of the security system **100** to protect the flow of their data. By labeling a resource with a particular taint **210**, a first user can assert control over the flow of information from that resource. The first user can grant a first set of other users the right to initiate information flows from the resource, and can grant a second set of other users the right to take information from the resource out of the network.

As discussed above in detail, various exemplary embodiments of the present invention can provide an effective means to reduce or prevent data leaks in an enterprise network, by requiring information flows to comply with applied resource labels. While security systems and methods have been disclosed in exemplary forms, many modifications, additions, and deletions may be made without departing from the spirit and scope of the system, method, and their equivalents, as set forth in the following claims.

What is claimed is:

1. A security system for a plurality of resources in a computer network having a plurality of hosts, the security system comprising:

a computer processor;

a memory operatively coupled to the computer processor and configured for storing data and instructions;

a plurality of taints, each taint configured to be applied by a labeling system to at least one of the plurality of resources, and each taint having a plurality of characteristics including identification data, secrecy data, and integrity data, the characteristics variably being in a first state or a second state;

a plurality of labels, each label comprising at least one taint;

the labeling system in communication with the plurality of hosts and configured to apply, by the processor, a label of the plurality of labels to a corresponding operating system resource of the plurality of resources, and to receive notifications of attempted writes to the operating system resource, wherein the operating system resource includes one or more of a file, process, socket, thread, or memory page;

a capability database configured for associating each of a plurality of users with a respective corresponding capability set for each respective taint of the plurality of taints, wherein according to a first capability set of a first user for a first taint, the first user has a capability to change the characteristics of the first taint from the second state to the first state, and from the first state to the second state, in the first label,

wherein the labeling system is further configured to automatically modify the state of the first label on behalf of the first user, to facilitate the information flow; and

an enforcement system in communication with the plurality of hosts and configured to block outgoing computer network traffic from each host, responsive to determining the outgoing computer network traffic includes a first resource where at least one taint in a first label of the first resource is in the first state.

2. The security system of claim **1**, the enforcement system being configured to block an information flow from the first resource having the first label to a second resource having a second label, responsive to determining the first label comprises a first taint with characteristics in the first state and the second label lacks the first taint with characteristics in the first state.

3. The security system of claim **2**, the labeling system applying an immutable label to the second resource, wherein the second resource leads outside the computer network.

4. The security system of claim **2**, the enforcement system being configured to block the information flow to the second resource absent content-scanning of the information flow.

5. The security system of claim **2**, the enforcement system being configured to determine provenance of the first resource based on the first label having the first taint with characteristics in the first state.

6. The security system of claim **1**, wherein according to a second capability set of a second user for the first taint, the second user lacks the capability to change the characteristics of the first taint from the second state to the first state.

7. The security system of claim **1**, the plurality of resources comprising a plurality of database entries, wherein the labeling system is configured to apply a corresponding label to each of the plurality of database entries.

8. The security system of claim **7**, wherein the computer network is an enterprise network, the enforcement system being further configured to identify login credentials of users who access a database from locations external to the enterprise network, and to selectively allow authorized users to retrieve the database entries from locations external to the enterprise.

9. A security system for a plurality of resources in a computer network having a plurality of hosts, the security system comprising:

a computer processor;

a memory operatively coupled to the computer processor and configured for storing data and instructions;

a plurality of taints, each taint configured to be applied by a labeling system to at least one of the plurality of resources, and each taint having a plurality of characteristics including identification data, secrecy data, and integrity data, the characteristics variably being in a first state or a second state;

a plurality of labels, each label comprising at least one taint;

the labeling system in communication with the plurality of hosts and configured to apply, by the processor, a label of the plurality of labels to a corresponding operating system resource of the plurality of resources, and to receive notifications of attempted writes to the operating system resource, wherein the operating system resource includes one or more of a file, process, socket, thread, or memory page;

a capability database configured for associating each of a plurality of users with a respective corresponding capability set for each respective taint of the plurality of taints, wherein according to a first capability set of a first user for a first taint, the first user has a capability to change the characteristics of the first taint from the second state to the first state, but not from the first state to second state, in the first label,

wherein the labeling system is further configured to automatically modify the state of the first label on behalf of the first user, to facilitate the information flow; and

an enforcement system in communication with the plurality of hosts and configured to block outgoing computer network traffic from each host, responsive to determining the outgoing computer network traffic includes a first resource where at least one taint in a first label of the first resource is in the first state.

10. The security system of claim **9**, the enforcement system being configured to block an information flow from the first resource having the first label to a second resource having a second label, responsive to determining the first label comprises a first taint with characteristics in the first state and the second label lacks the first taint with characteristics in the first state.

11. The security system of claim **9**, the labeling system applying an immutable label to the second resource, wherein the second resource leads outside the computer network.

12. The security system of claim **9**, the enforcement system being configured to block the information flow to the second resource absent content-scanning of the information flow.

13. The security system of claim **9**, the enforcement system being configured to determine provenance of the first resource based on the first label having the first taint with characteristics in the first state.

14. The security system of claim **9**, wherein according to a second capability set of a second user for the first taint, the second user lacks the capability to change the first taint from the second state to the first state.

15. The security system of claim **9**, the plurality of resources comprising a plurality of database entries, wherein the labeling system is configured to apply a corresponding label to each of the plurality of database entries.

16. The security system of claim **15**, wherein the computer network is an enterprise network, the enforcement system being further configured to identify login credentials of users who access a database from locations external to the enterprise network, and to selectively allow authorized users to retrieve the database entries from locations external to the enterprise.

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